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Nonequilibrium superconductivity in microwave field (*)

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Résumé. — On a effectué l'étude expérimentale et théorique de la supraconductivité hors équilibre d'échantillons longs, étroits ($L > \xi(T)$) et courts ($L < \xi(T)$) en Sn, In, Al en présence de champs alternatifs de fréquences comprises entre 7 Mc et 150 Gc. On a établi les lois principales auxquelles obéissent la stimulation et la suppression de la supraconductivité en fonction des dimensions, du matériau et de la pureté des échantillons. On propose une méthode de détermination du temps de relaxation non élastique τ_e . On a déterminé $\tau_e = 8,3 \times 10^{-10}$ s pour Sn et $\tau_e = 4,62 \times 10^{-9}$ s pour Al. On montre que les résultats expérimentaux sont en bon accord avec les théories d'Eliashberg et d'Aslamazov-Larkin.

Abstract. — The nonequilibrium superconductivity of narrow long ($L > \xi(T)$) and short ($L < \xi(T)$) samples of Sn, In, Al has been studied in the frequency range of 7 Mc to 150 Gc. The principal regularities for stimulation and suppression of superconductivity and their dependence on the sample dimension, material and purity have been found. A method for estimating the inelastic relaxation time, τ_e , is proposed. It has been found that for Sn $\tau_e = 8.3 \times 10^{-10}$ s and for Al $\tau_e = 4.62 \times 10^{-9}$ s. The experimental data are in good agreement with the Eliashberg and the Aslamazov-Larkin theories.

It is shown that microwave-induced nonequilibrium superconductivity has common regularities for long uniform channels and bridges of the dimension $L > \xi(T)$. At frequencies of ~ 10 Mc and lower, the superconductivity is suppressed as the radiation power rises by the law $I_c(P) \neq I_c(0) \left[1 - \frac{P}{P_c}\right]^{3/2}$ resulted from the Ginzburg-Landau mechanism of pair breaking. When we increase the frequency, this law is disturbed, and the current $I_c(P)$ is suppressed less and less until it reaches $I_c(0)$ due to the radiation effect. As the frequency increases further,

$$I_c(P) > I_c(0).$$

Such a frequency is the lower critical frequency ω_1 of the effect $I_c(P) > I_c(0)$. With further increasing frequency, this effect reaches a maximum at the optimal frequency ω_0 , then reduces and vanishes at the upper critical frequency ω_2 . Under radiation, not only does the critical current increase, but the critical temperature T_c increases by the value $\Delta T_c(P)$. In the Eliashberg technique [1] for order parameter Δ one can get the following equation at zero current through the sample [2] :

$$t = 1 - 0.1066 \alpha^2 - \mathcal{D} \left\{ \frac{1.195 \times 10^{-11} (1 + b^2)}{T_c \tau_e} + 0.173 \Omega^2 - 0.25 \frac{\Omega^2}{\alpha} \left[\ln \left(\frac{8\alpha}{\Omega} \right) - 1 \right] \right\}, \quad (1)$$

where

$$\alpha = \frac{\Delta}{kT_c}, \quad \Omega = \frac{\hbar\omega}{kT_c}, \quad t = \frac{T}{T_c}, \quad \mathcal{D} = \frac{\alpha}{\gamma},$$

$$\gamma = \frac{\hbar}{\tau_e}, \quad \alpha = \frac{1}{3} \mathcal{V}_F l e^2 A^2 \omega / \hbar c^2,$$

b^2 -characterizes the constant magnetic field. Differentiating exp. (1) with respect to Ω and α , an expression can be found which determines the optimal frequency Ω_0 and jump α_0 :

$$\ln \left(\frac{8\alpha}{\Omega_0} \right) = 1.5 + 0.22 \pi \alpha, \quad (2)$$

$$\frac{21 \zeta(3)}{8 \pi^2} \cdot \Omega \cdot \left(\frac{2\alpha_0}{\Omega} \right)^3 =$$

$$= \mathcal{D} \left[3(2 - \ln 4) - \ln \left(\frac{2\alpha_0}{\Omega} \right)^3 \right]. \quad (3)$$

Equations (2) and (3) present the interaction between the corresponding parameters; to determine the temperature, the parameters should be substituted in (1). The calculated results of frequencies f_1, f_0, f_2

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and of Δ , expressed in frequency, are shown for Sn specimens in figure 1, where are plotted both our experimental data and those from the literature.

Fig. 1.

In the calculations we use the following values : $\Delta = 3.063 \times kT \sqrt{1-t}$ (the equilibrium value), $T_c = 3.8$ K, $\tau_e = 8.3 \times 10^{-10}$ s, $D = 0.15$. The studies of the mechanism of formation of the lower (ω_1) and the upper (ω_2) critical frequencies make it possible to determine the time τ_e by measuring the frequency ω_1 for the effect $I_c(P) \geq I_c(0)$; for Al, $\tau_e = 4.62 \times 10^{-9}$ s.

As one can see from (1) the phase transition in the nonequilibrium case is the first-order transition with respect to the Δ jump. It seems that there is a critical current jump also at the transition point with the microwave radiation [2, 4, 5]. To make this clear, in the Ginzburg-Landau technique we have written the following equation for nonequilibrium supercurrent

$$j_s = B \cdot \alpha^2 \cdot \left\{ 1 - t - 0.1066 \cdot \alpha^2 - D \left[\frac{1.195 \times 10^{-11}}{T_c \tau_e} + 0.173 \Omega^2 - 0.25 \frac{\Omega^2}{\alpha} \left(\ln \left[\frac{8\alpha}{\Omega} \right] - 1 \right) \right] \right\}^{1/2}, \quad (4)$$

where

$$B = \frac{em^2 v_F \sqrt{D}}{\sqrt{2} \pi^3 \hbar^7} \cdot (kT_c)^{3/2},$$

and have studied it carefully together with (1). It is seen from the depairing curves, figure 2, that the only difference between the equilibrium and nonequilibrium cases is that the critical current goes to zero at $\Delta = 0$ for the first case and at Δ , corresponding to the value of Δ jump, for the second case. But for both cases the critical current increases from zero continuously. Figure 3 shows the increase of I_c and T_c at 15.6 Gc. In our opinion the experimental current jumps are due to the influence of rf heat. The comprehensive experimental study of $R(P)$ and $\frac{d\alpha}{dD} \bigg|_{D \rightarrow 0} (T)$

Fig. 2.

dependences near T_c indicates that there are small maxima on these dependences which do not follow from (1). It should be noted that the conditions under which the deviations from (1) are observed correspond to those in which $L < \xi(T)$. Hence, very short In bridges which displayed the AC Josephson effect near T_c were studied experimentally. For these specimens the stimulation of superconductivity was observed only at $T < T_c$ while near T_c it was suppressed. In [6] the effect of microwave radiation on the critical current of nonuniform junctions was considered and the equations were obtained for the effect the physical nature of which is the change in the electron distribution function due to the energy diffusion of electrons when they are reflected again from the potential well edges in the microwave field. The experimental results for nonuniform bridges are in satisfactory agreement with the theory [6]. The oscillations of the electrons in the potential well facilitate the energy diffusion, and this may explain

Fig. 3.

the fact that the stimulation of superconductivity in nonuniform junctions can be observed much easier than in uniform junctions. The effect of material parameters (mean free path l and Fermi velocity v_F) on the superconductivity stimulation has been analysed. For long specimens the stimulation is shown

to be more effective at large l and v_F and for short specimens to be more effective at small l .

In conclusion, the effect found in [7] is shown to be due to the influence of microwave radiation on the electron distribution function in agreement with the results from [1, 6].

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